SCHLIEREN STUDY OF
COMPOSITE PROPELLANT COMBUTION

Robert Ross Gerhardt

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

SCHLIEREN STUDY
OF
COMPOSITE PROPELLANT COMBUSTION

by

Robert Ross Gerhardt
Lieutenant, United States Navy
B.S., Naval Postgraduate School, 1973

Thesis Advisor: D. W. Netzer

March 1974

Approved for public release; distribution unlimited.

Schlieren Study
of
Composite Propellant Combustion

by

Robert Ross Gerhardt
Lieutenant, United States Navy
B.S., Naval Postgraduate School, 1973

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
March 1974

ABSTRACT

A photographic investigation of metallized and non-metallized composite solid propellant combustion was made. Propellant strands made from large unimodal AP and PBAN binder, both with and without aluminum powder, were burned in a conventional stainless steel combustion bomb. High speed color schlieren motion pictures were taken of the combustion process to determine the effects of pressure and strand thickness on propellant deflagration. Results are discussed and compared with data on AP/binder sandwich experiments.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENT

I would like to acknowledge the help of Professor D. W. Netzer and Mr. Edward Michelson for their advice and assistance throughout the length of this project. Appreciation is also expressed to Mr. Glen Middleton for his expertise in the fabrication of the high pressure stainless steel combustion bomb.

I. INTRODUCTION

Numerous analytical and experimental studies of composite solid propellant combustion utilizing ammonium perchlorate (AP) as the oxidizer have been made. The combustion process involves a very complex set of concurrent reactions taking place in the gas, liquid, and solid phases of the heterogeneous propellant mixture. Past studies, e.g., Boggs and Zurn (1), Murphy and Netzer (2), and others have concentrated on AP crystal and AP/binder sandwich combustion because of the ease of visual study of the resulting two-dimensional flame under a wide range of experimental environments.

The approach to AP/binder sandwich and composite propellant research has been two-fold. For example, Hightower and Price (3), Derr and Boggs (4), and others have utilized high speed motion picture photography and post-fire examination of rapidly quenched samples with a scanning electron microscope. The application of this technique has disclosed the presence of binder flow onto the AP surface, the existence of an AP froth or melt, and the effect of pressure and binder type on the surface structure.

The second approach to AP/binder sandwich deflagration was the color schlieren inspection of the gas phase interactions during propellant combustion, e.g., Murphy and Netzer (2) and Kennedy, et al (5). In these studies, behavior observed by the examination of the temperature profile in the gas phase apparently agreed with the AP/binder sandwich behavior postulated from quenched sample data.

These past studies have yielded much usable data concerning flame type (premixed or diffusion) and flame characteristics (steady, unsteady, laminar, or turbulent) in the combustion of composite solid propellants. There were, however, three distinct problems encountered in the schlieren

studies which warrant further attention. First, results obtained have been limited to pressures below 1,000 psi due to the pressure limits on the combustion bomb. Second, the 1,000 watt mercury vapor arc schlieren light source was overpowered by the visible yellow flame given off during propellant deflagration. Third, no study correlating three-dimensional real propellant combustion and two-dimensional AP/binder sandwich combustion has been documented.

In response to the first problem a combustion bomb capable of pressures to 3,000 psi was designed and fabricated for future study at pressures beyond 1,000 psi.

Klahr (6), in order to overcome the second problem, experimented with laser schlieren. Good schlieren resolution was obtained in which the visible flame light was effectively eliminated, but two major problems were encountered: the characteristic speckle associated with laser holography, and an unacceptable diffraction pattern caused by the knife edge. Klahr used both a solid knife edge and a neutral density filter. The solid knife edge proved unsatisfactory in all laser power ranges. The neutral density filter provided excellent results at low laser power but at high power its metallic coating was burned by the laser beam. For future study by this method it will be necessary to use a single crystal quartz prism or similar device for the knife edge.

The purpose of this investigation, in response to the third problem discussed above, was to compare the combustion behavior of real three-dimensional metallized and non-metallized composite solid propellants with that of two-dimensional AP/binder sandwiches.

II. METHOD OF INVESTIGATION

The investigation consisted of high speed color motion picture studies, in both regular and schlieren light, of the deflagration of both non-metallized and metallized composite solid propellants in the strand configuration. Both propellants, fabricated by the Naval Weapons Center, had large unimodal distributions of ammonium perchlorate (AP) in PBAN binder.

In an attempt to determine the minimum thickness at which deflagration would occur, thereby reducing the visible yellow light to a minimum, the strand thickness for the non-metallized propellant was varied from 762 microns to 1270 microns (.030 to .050 inches). For the metallized propellant this dimension ranged between 355 microns and 889 microns (.014 to .035 inches).

The schlieren studies were conducted in both a nitrogen purged and an air purged combustion bomb at pressures ranging from atmospheric to 500 psig.

High speed color motion pictures were taken of the propellant deflagration at the various pressures and thicknesses. Because of the light source chopper utilized, the films were composed of alternating frames of color schlieren and standard real-light color pictures. These motion pictures were studied to determine the effects of pressure on the burning strand surface. In particular, local deflagration phenomena of the AP crystals and overall binder melt flow across the deflagrating surface were studied for comparison with AP/binder sandwich results.

III. EXPERIMENTAL PROCEDURES AND APPARATUS

A. PROPELLANT SPECIFICATIONS AND FABRICATION

Specifications for the propellants utilized in this investigation are summarized in Table I. Both the non-metallized N-3 and the metallized N-8 employed unimodal distributions of AP. The AP, supplied by American Potash & Chemical Corporation, was passed through a Tyler #32 mesh (500 microns) and what remained on a Tyler #35 mesh (420 microns) was used. In addition, the aluminum powder incorporated in propellant N-8 was type H-30 and was passed through a Tyler #325 mesh (44 microns). A weight ratio of 79 parts AP to 21 parts PBAN was maintained in both propellants. Figure 1 is a 56X micrograph of the N-3 propellant showing the large AP crystals.

In order to reduce the amount of visible yellow light given off during deflagration and to minimize "schlieren averaging," propellant strands were kept as thin as possible. The N-3 propellant strand thickness (see Figure 2 for other dimensions) was varied from .030 to .050 inches. This thickness variation corresponded to a thickness where no useful data was obtainable due to the overpowering visible light to a thickness where deflagration could not be sustained. For the N-8 propellant, similar thicknesses were .014 to .035 inches. The burner "mini-strands" were shaved from a block of propellant with a razor blade, trimmed to size, and mounted on end on stainless steel pedestals with Testors glue. Measurements for height, width, and thickness were made with a Gaertner Scientific Corporation microscope.

B. COMBUSTION BOMBS AND SCHLIEREN

Details of the combustion bomb are discussed in Reference 5. Reference 2 contains refinements made on the schlieren resolution and experimental

apparatus. Figure 3 is a schematic of the combustion bomb and schlieren system used in this investigation and Table II lists and describes the equipment.

The critical straight-line alignment of the light source, lenses, combustion bomb, and high speed camera was accomplished using an Optics-Technology He-Ne laser.

Pressurization of the combustion bomb, ignition of the propellant strands, and activation of the high speed camera were controlled from behind a steel safety shield with plexiglass viewing ports.

In order to continue the experimental evaluation of both AP/binder sandwiches and composite solid propellants beyond the pressure capability of the current system, a high pressure combustion bomb was designed and fabricated. Composed of 347 stainless steel, this bomb will operate to pressures of 3,000 psi. It has a core volume of about 34 cubic inches with a .375 inch diameter inlet port at the bottom and a similar sized exhaust port at the top for the high pressure nitrogen purge system. Integral provisions for mounting the burner strands and for hot wire ignition were incorporated. Figure 4 is a photograph of the combustion bomb. Figure 5 is a schematic showing major dimensions of the two-piece high pressure unit. Three optical quality glass windows, one inch in diameter, were incorporated in the bomb. Two windows, located diametrically opposite each other, will be utilized for laser schlieren and cinematographic observation of the burning specimens. The third window, located at 90° between the other two, will be utilized for side lighting and for remote viewing.

Parker O-ring static pressure seals with one back-up ring were used around the windows and at the junction of the two-piece unit.

C. PROPELLANT TESTING

The prepared specimens were taken from storage in a dessicator jar and were set in the pedestal holder in the combustion bomb. The schlieren system was checked for alignment, an ignition wire was attached, and the combustion bomb was sealed. The red and blue filter matrix was checked for proper alignment, the light source chopper and side light were activated, and the bomb was pressurized to the desired pressure from behind the safety shield. At this point, ignition was initiated, and if successful, the camera was activated to record the results of the burn.

Ignition was accomplished with a doubly twisted nichrome resistance wire placed in contact with the top surface of the propellant strand. Current through the ignition wire was regulated so that ignition wire burn-out did not occur prior to propellant ignition.

IV. RESULTS AND DISCUSSION

A. GENERAL DISCUSSION

Multiple tests were conducted at pressures of one atmosphere, 100 psig, and 500 psig for both propellants. The principal medium utilized for the high pressure purge of the combustion bomb was nitrogen, although dry air was also used for several runs at the lower pressures. All strand ignition was accomplished by carefully placing doubly-twisted nichrome resistance wire in contact with the upper surface of the propellant strands.

The direct ignition wire contact with the strand surface proved to be the most effective method. Past AP/binder sandwich studies utilized a mixture of black powder and glue placed on the ignition wire for an even ignition across the top surface of the strand. This procedure did not prove satisfactory for either the N-3 or the N-8 propellant for two reasons: (1) the very thin propellant strands did not offer a sufficiently broad base upon which to place the relatively large black powder grains nor were they able to sustain weight without lateral bending and bowing, and (2) the acetone, utilized in softening the black powder/glue mixture for application on the ignition wire, saturated the top portion of the strand causing it to deteriorate and bend away from the ignition wire.

Although the propellant strands burned more evenly, no useful data were obtained from the experiments when air was utilized as the high pressure purge medium because of the overpowering yellow flame light.

B. NON-METALLIZED PROPELLANT N-3

While attempting to minimize the intensity of the visible yellow light by using very thin propellant strands, other problems were encountered.

The strands had very little longitudinal stiffness as discussed above. In addition, when the thickness of the N-3 propellant strand fell below .034 inches, ignition attempts were unsuccessful at any pressure. In these "no burn" situations, visual light sputter was evident at time of ignition but sustained deflagration was not obtained. These propellant "mini-strands" were apparently quenched by heat loss from the surface to the purge medium and/or by ignition induced binder flow and/or by surface starvation of AP. Examination of the strands after unsuccessful ignition showed evidence that deflagration had occurred. Black charred pockets were evident along the top surface. Examination of these pockets with a microscope revealed a glazed-over surface lining the pocket, presumably formed by cooled binder melt. Seldom were any AP crystals observed protruding from the top surface of these strands. In addition, ignition attempts with these "mini-strands" of N-3 propellant at 500 psig were totally unsuccessful, even at thicknesses of .040 inches. Experiments with conventional strand dimensions were not practical because of the schlieren light being overpowered by the yellow flame light.

Several strand shapes were tested in an attempt to obtain strands which would burn with a thickness less than .034 inches. Two of the cross-sections employed were an I-beam and a T shape. Various wedge shapes were also tried. Although significantly thinner strand portions were successfully ignited and burned, no usable data were obtained because of uneven surface burning and excessive luminosity above the thicker portions of the strands.

Figure 6 contains a time sequence of propellant N-3 at 100 psig. Even with the thin strands, schlieren information is minimal with the 1,000 watt light source. It is apparent from these photographs that surface regression was non-uniform. In Figure 6(a), taken shortly after ignition, the

deflagration is well-established, with high, closed flames around the AP crystals, and binder melt is evident along most of the upper edge. In Figure 6(b) the more uniformly distributed flames have transitioned to individual flames around each of the AP crystals. In Figure 6(c), the deflagration on the right half of the strand has ceased and the binder appears to be flowing from right to left. It is believed this quenching is caused by binder melt flow over the AP crystals.

Figure 7 shows a color schlieren photograph taken of N-3 at 100 psig. Surface burning is again very uneven. An area of binder melt appears as a black patch near the upper right corner of the propellant strand. Individual AP crystals can be seen as glowing hemispheres with a closed flame around and above each one. The characteristic alternating red and blue zones are apparent and show the temperature gradients in the gas phase above the deflagrating surface.

Propellant N-3 typically displayed very irregular burning. As a single AP crystal first became exposed on the surface it would burn with several individual flamelets around its periphery. As the binder melt dissipated and exposed more of the AP surface, the flamelets merged to form a closed flame over the oxidizer crystal. This is opposite to the behavior observed in the AP/binder sandwich experiments. Binder melt appeared to be appreciable, with occasional evidence of distinct flow over some of the surface. The flames were laminar, in agreement with AP/binder sandwich flames. Thus, at low pressures there are distinct differences between AP/binder sandwich deflagration and normal propellant combustion. The excess oxidizer present in sandwich burners apparently causes the visible diffusion flames to close above the binder whereas in propellant combustion the flame closes above the oxidizer crystal. The closed diffusion flame above the oxidizer particle

is in agreement with the model proposed by Beckstead, Derr, and Price (7). However, the transition to a premixed flame at low pressures proposed in the model apparently occurs below 100 psi. Surface irregularities caused by the varying AP size and the basic inhomogeneity of the propellant also appear to cause more binder melt interaction with the AP in propellant combustion than in sandwich deflagration. The binder flow differences may become even more significant at higher pressures where the AP crystals are recessed below the surface.

C. METALLIZED PROPELLANT N-8

The metallized N-8 propellant "mini-strands" ignited and burned much more readily than non-metallized N-3 propellant. Strands with thicknesses of .012 inches were successfully ignited but the deflagration was very sporadic and uneven. A compromise between excessive luminosity and sporadic burning was found at a strand thickness of .021 inches for the N-8 propellant. The longitudinal stiffness problem was even more critical with this propellant. The improved burning qualities of the N-8 were attributed to the additional energy given off by the uniformly distributed aluminum particles.

The hot aluminum particles apparently attracted each other and they formed into agglomerates which grew in size until drag forces from the rising hot gases forced them off the deflagrating surface. As they detached, they tended to pull smaller hunks and particles with them in their wake. (The schlieren was again difficult to evaluate because of the additional luminosity provided by the burning aluminum powder in the propellant.) In general the burning AP crystals remained on the surface of the strand longer than did the aluminum agglomerates.

Figure 8 is a color schlieren photograph of N-8 propellant taken at 500 psig. The surface is more non-uniform and the gases above the surface are more turbulent than at 100 psig, but the various reaction sites on the strand surface can still be distinguished by alternating red and blue patterns. A binder protrusion is present in the middle of the strand and a patch of binder melt is located at the right corner.

At 500 psig, the schlieren above the deflagrating surface of the composite propellant portrays the same surface generated "turbulence" as that found in AP/binder data at this pressure. Also, the binder protrusion in Figure 8 is characteristic of sandwich deflagration at high pressures.

Figure 9a and 9b are photographs of N-8 propellant at 100 psig in normal photography and color schlieren, respectively. Flame configuration is similar to the non-metallized N-3 results with closed flames above the AP crystal. A glowing aluminum agglomerate is positioned to the left of the strand center and individual AP crystals are seen to the right.

There appears to be more flow of the binder melt on both propellants N-3 and N-8 than on AP/binder sandwiches. These observations lend support to the proposal (Ref. 8) that binder flow causes burning rate acceleration sensitivity in both non-metallized and metallized propellants.

V. CONCLUSIONS

This section presents the conclusions reached from this investigation of composite propellant combustion.

1. As an AP crystal is first exposed to the burning surface, small individual flamelets exist around its periphery. At low pressures, as the AP crystals protrude above the surface, the flamelets merge to form a closed diffusion flame over the AP. This is in agreement with the model of Beckstead, Derr, and Price (7) but opposite to the results for AP/binder sandwich deflagration where the diffusion flames at low pressure close above the binder protrusion.

2. Distinct diffusion flames exist above the AP crystals to pressures as low as 100 psi.

3. Binder flow appears to occur more readily in propellant combustion than in AP/binder sandwich deflagration and causes local surface quenching.

4. At 500 psi, propellant combustion yields the same surface generated "turbulence" as found in AP/binder sandwich deflagration.

6. More powerful (greater than 1,000 watt) arc-lamps or laser sources will be required for schlieren studies of propellant combustion at high pressures.

LIST OF REFERENCES

1. Boggs, T.L. and Zurn, D.E., "The Deflagration of Ammonium Perchlorate Polymeric Binder Sandwich Models," Comb. Sci. and Tech., v. 4, 1972, p. 279-292.

2. Murphy, J.L. and Netzer, D.W., "Ammonium Perchlorate and Ammonium Perchlorate-Binder Sandwich Combustion," Naval Postgraduate School Report No. NPS-57Nt73021A, February 1973.

3. Hightower, J.D. and Price, E.W., "Experimental Studies Relating to the Combustion Mechanism of Composite Propellants," Astronautica Acta., v. 14, 1968, p. 11-21.

4. Derr, R.L. and Boggs, T.L., "Role of Scanning Electron Microscope in the Study of Solid Propellant Combustion: Part III. The Surface Structure and Profile Characteristics of Burning Composite Solid Propellants," Comb. Sci. and Tech., v. 1, 1970, p. 369-384.

5. Netzer, D.W., Kennedy, J.R., Biery II, G.M., and Brown, W.E., "Non-Metallized Composite Propellant Combustion," Naval Postgraduate School Report No. NPS-57Nt72031A, March 1972.

6. Klahr, O.A., "Application of Laser Schlieren and Monochromatic Photography to Solid Propellant Combustion Research," Masters Thesis, Naval Postgraduate School, December 1973.

7. Beckstead, M.W., Derr, R.L., Price, C.F., "A Model of Composite Solid Propellant Combustion Based on Multiple Flames," AIAA Journal, v. 8, no. 12, October 1970, p. 2200-2207.

8. Cowles, D. and Netzer, D., "The Effect of Acceleration on Composite Propellant Combustion," Comb. Sci. and Tech., v. 3, 1971, p. 215-229.

TABLE I

COMPOSITE PROPELLANT FORMULATIONS

Propellant designation	AP size (microns)	Weight %AP	Weight %PBAN	Weight %Aluminum	Aluminum size (microns)
N-3	unimodal 420	79.00	21.00	----	----
N-8	unimodal 420	67.00	18.00	15.00	44

TABLE II

LIST OF EXPERIMENTAL EQUIPMENT

Schlieren light source	1000 watt mercury vapor arc lamp
Light source chopper location on bench	Directly in front of mercury arc lamp
External light source	1200 watt SLM-1200 projector
Knife edge	Vertical blue and red filter matrix
Focusing lens	610 mm, f6
Framing rate	7500 FPS
Camera shutter	1/2.5
Color film	Kodak Ektachrome 7241
Ignition source	12 volt battery
Ignition wire	Nichrome resistance wire, 0.008 inch dia.

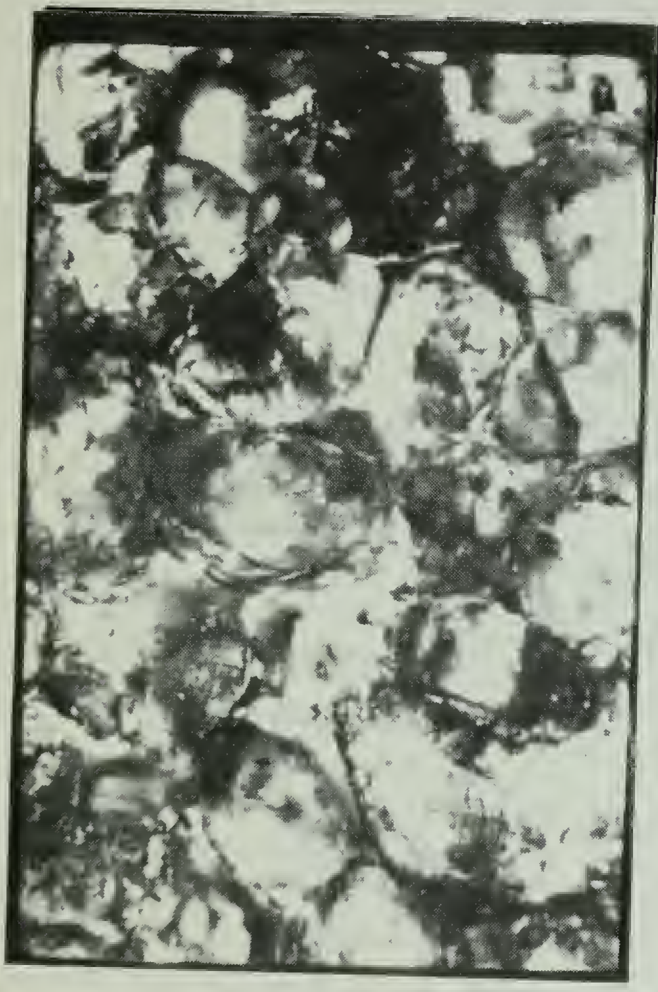
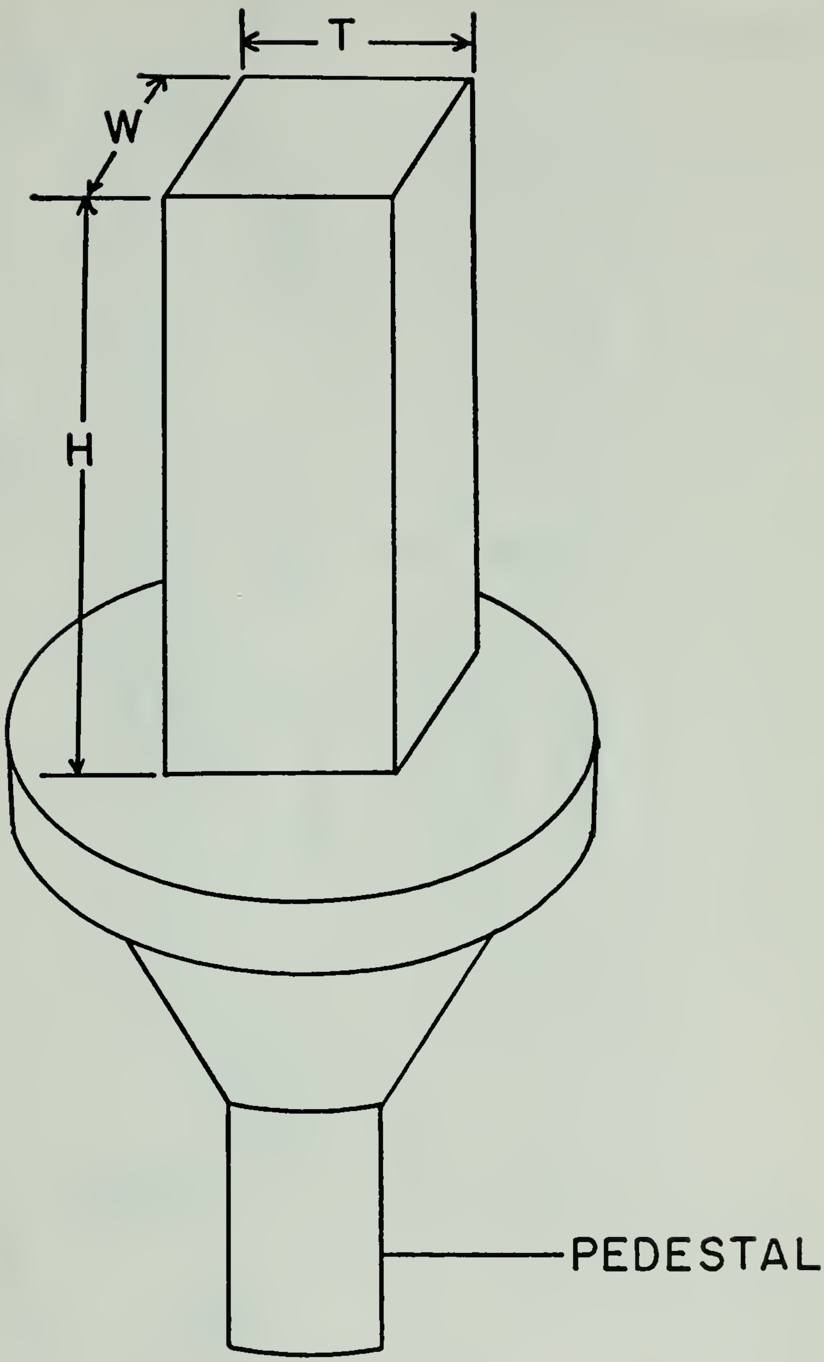


Figure 1

Micrograph of N-3 Propellant at 56X



HEIGHT	0.25	to	0.375
WIDTH	0.18	to	0.23
THICKNESS	0.012	to	0.050

FIGURE 2. Propellant Strand Dimensions

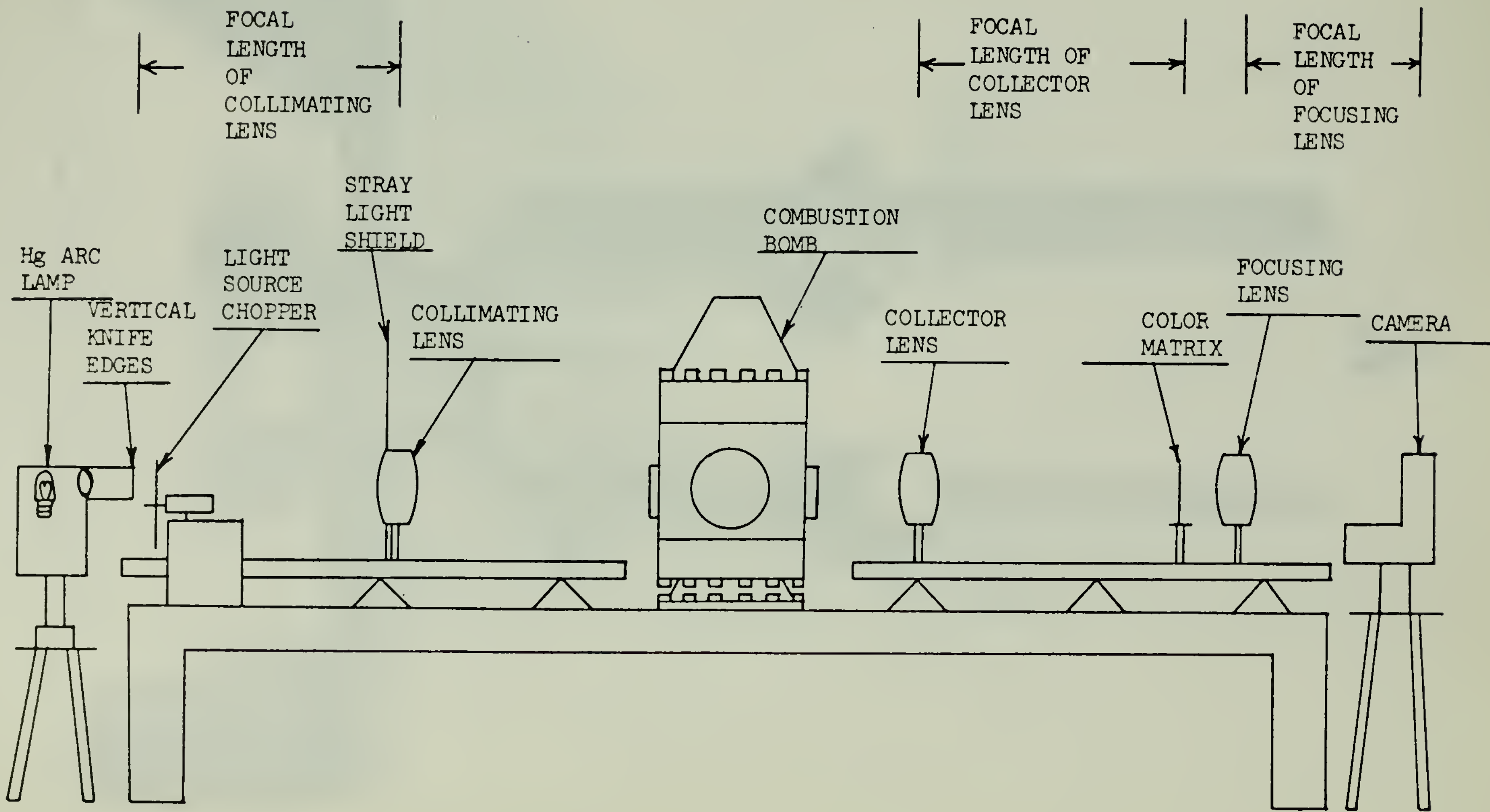


Figure 3. Schematic of Equipment Arrangement

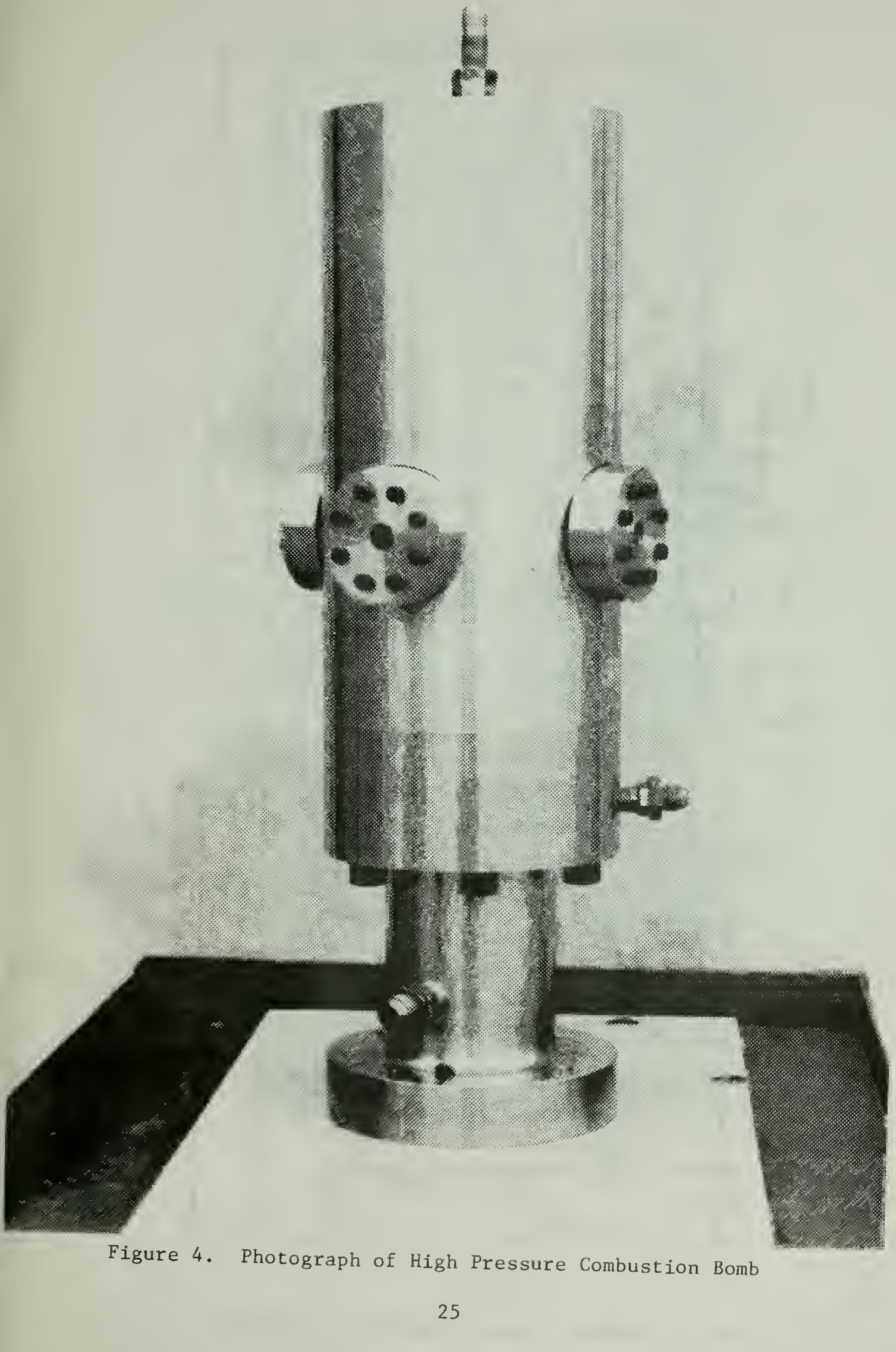


Figure 4. Photograph of High Pressure Combustion Bomb

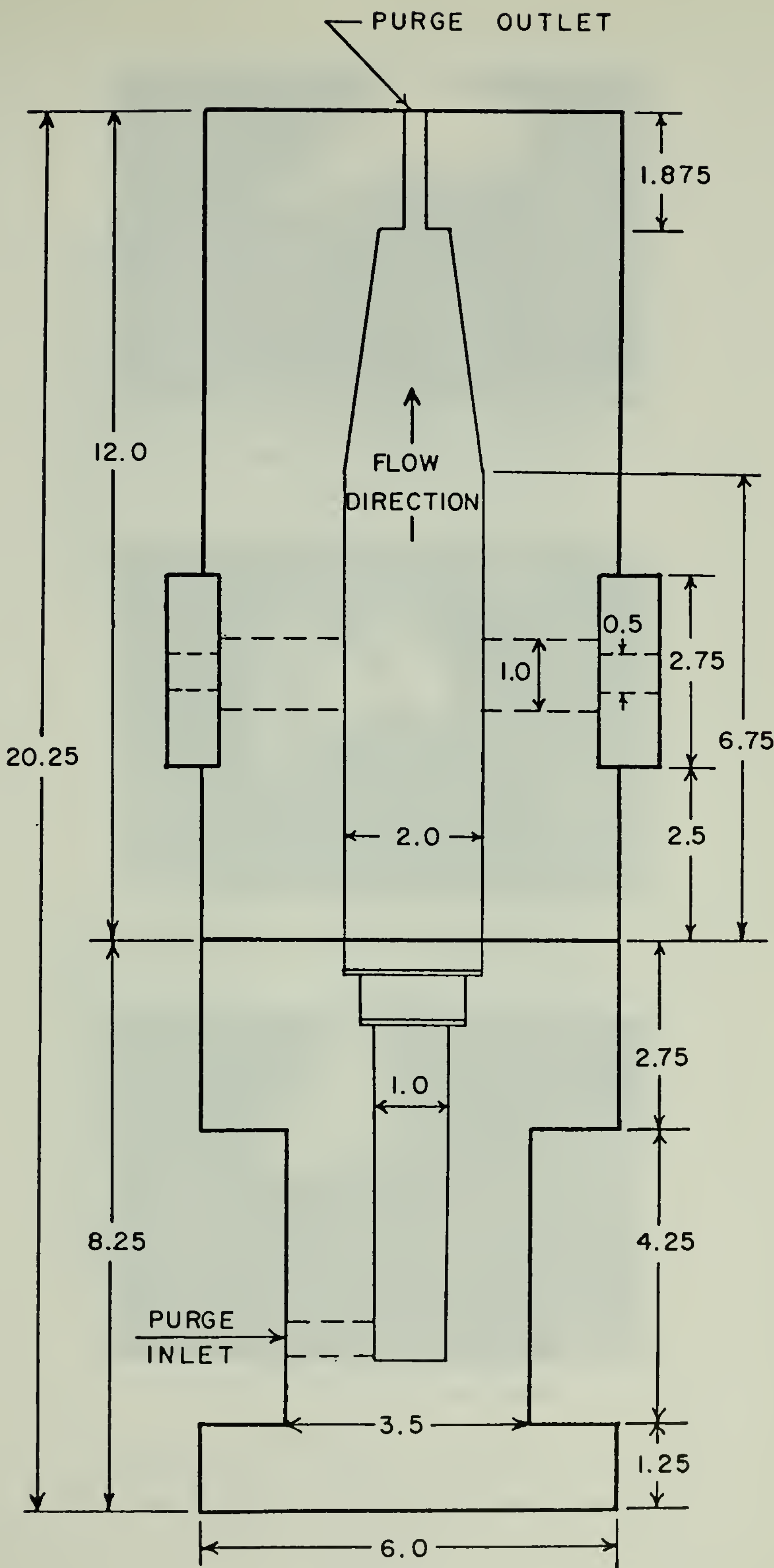
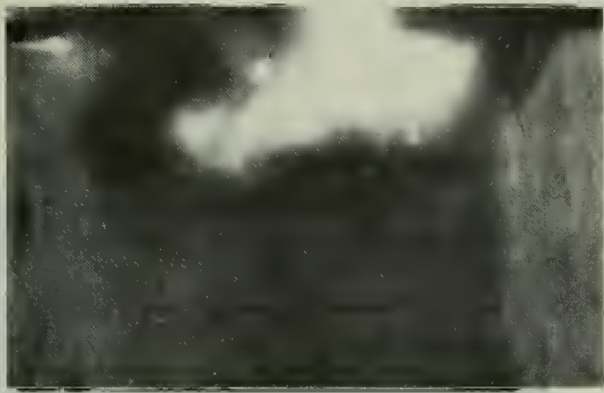
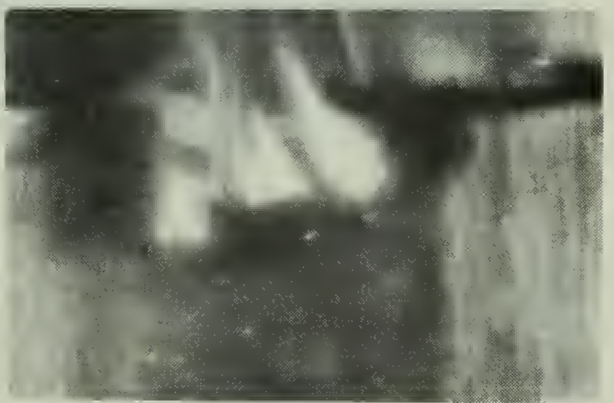


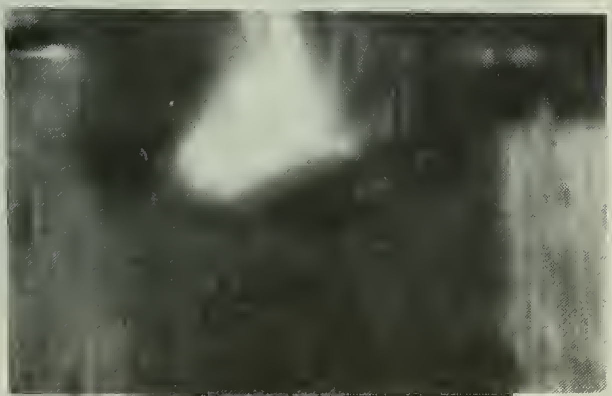
FIGURE 5
Schematic of High Pressure Combustion Bomb



(a) Time = 0 milliseconds

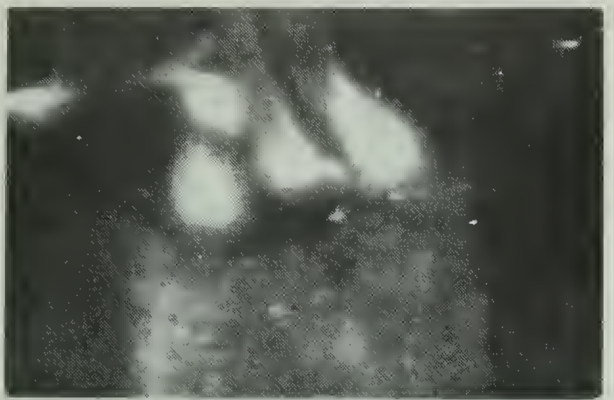


(b) Time = 27.2 milliseconds



(c) Time = 45.7 milliseconds

FIGURE 6
Time Sequence of N-3 Propellant
100 psig, .035 in. thick, .153 in. wide
Color Schlieren



(b) Time = 27.2 milliseconds

(c) Time = 45.7 milliseconds

FIGURE 6 (Con't.)
Time Sequence of N-3 Propellant
100 psig, .035 in. thick, .153 in. wide
Normal Photography

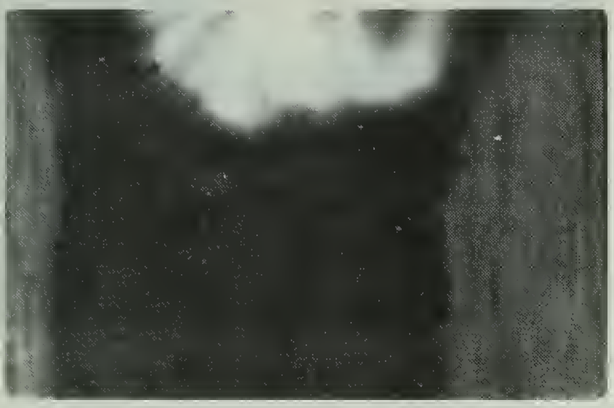


FIGURE 7
Color Schlieren of N-3 Propellant
100 psig, .036 in. thick, .175 in. wide

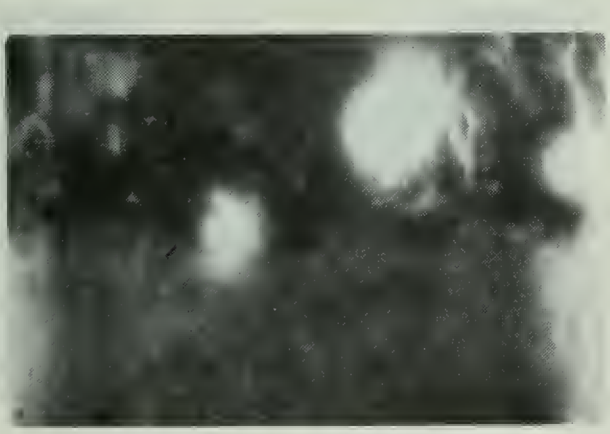


FIGURE 8
Color Schlieren of N-8 Propellant
500 psig, .022 in. thick, .215 in. wide

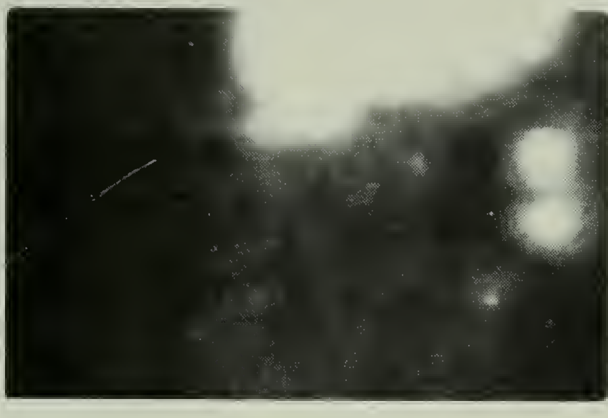


FIGURE 9a
Normal Photography of N-8 Propellant
100 psig, .025 in. thick, .192 in. wide

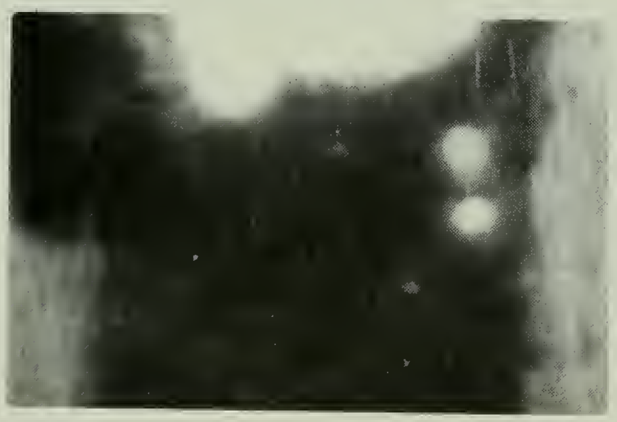
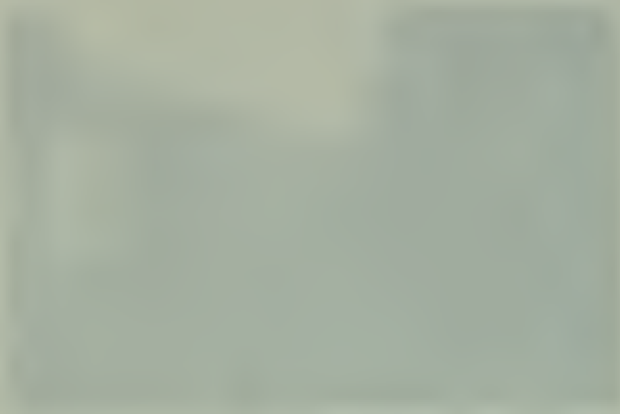


FIGURE 9b
Color Schlieren of N-8 Propellant
100 psig, .025 in. thick, .192 in. wide



INITIAL DISTRIBUTION LIST

		No. copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0212 Naval Postgraduate School Monterey, California 93940	2
3.	Assoc. Professor D. W. Netzer Department of Aeronautics Naval Postgraduate School Monterey, California 93940	2
4.	Professor R. W. Bell Chairman, Department of Aeronautics Naval Postgraduate School Monterey, California 93940	1
5.	LT R. R. Gerhardt, USN 156 Cerro Street Encinitas, California 92024	2

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Schlieren Study of Composite Propellant Combustion		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; March 1974
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Robert Ross Gerhardt		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE March 1974
		13. NUMBER OF PAGES 33
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Naval Postgraduate School Monterey, California 93940		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Composite propellant

Combustion

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A photographic investigation of metallized and non-metallized composite solid propellant combustion was made. Propellant strands made from large unimodal AP and PBAN binder, both with and without aluminum powder, were burned in a conventional stainless steel combustion bomb. High speed color schlieren motion pictures were taken of the combustion process to determine the effects of pressure and strand thickness on propellant deflagration. Results are discussed and compared with data on AP/binder sandwich experiments.

DD Form 1473 (BACK)
1 Jan 73
S/N 0102-014-6601

Thesis
G325
c.1

150870

Gerhardt
Schlieren study of composite propellant combustion.